

## Evidence for compact dark matter in galactic halos

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**Abstract** . Clumped dark matter arises naturally within the framework of generic cosmological dark matter models. Invoking the existence of dark matter clumps can also solve many unexplained mysteries in astrophysics and geology or geophysics, e.g. the galactic gamma-ray halo and the periodic terrestrial flood basalt volcanic episodes. Clumped dark matter is dynamically stable to friction and will not heat the disk. Such clumps may have already been discovered in the form of dwarf spheroidals, and further searches are encouraged by the results of this paper.

**Keywords** . Dark matter, galactic halos, flood basalt volcanism.

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### 1. Clumping as a prediction of cosmological models

As the bulk of the matter in the Universe is dark, a better understanding through theoretical models is important, and much current activity is taking place in that direction. Undoubtedly, more significant than this would be the detection of this dark matter. Much progress is taking place, and it is possible that dark matter may have been already detected. A Gran Sasso group claims to have found anomalous signs of a 56 GeV dark matter candidate [1]. However, a definite confirmation of this is awaited.

As the visible matter clumps together to form stars, planets, etc. an interesting question is whether the dark matter also displays this tendency of clumping. Interestingly several dark matter models do suggest that clumps of dark matter arise naturally during the course of evolution of the universe. Silk and Stebbins [2] considered cold dark matter models with cosmic strings and textures appropriate for galaxy formation. They found that a fraction  $10^{-1}$  of the galactic halo dark matter may exist in the form of dense cores. These may survive up to mass scales of  $10^8 M_\odot$  in galaxy halos and globular clusters [2]. Analysing the stability of these clumps of dark matter, they found that the cores of these clumps will not be affected, although the outer layers may be stripped off by tidal forces. In the cosmic string

model, the clumpiness  $C$ , defined as the ratio of clumped matter concentration to normal concentration, of dark matter at the present epoch would be [2]

$$C \sim 10^{12} f_{cl} h^6 \Omega_0^3, \quad (1)$$

where  $f_{cl}$  is the fraction of dark matter in clumps,  $H$  is the Hubble parameter parametrised as  $100 h \text{ km/s Mpc}^{-1}$ , and  $\Omega_0$  is the closure energy density of the Universe.

Subsequently, Kolb and Tkachev [3] studied isothermal fluctuations in the dark matter density during the early universe. If the density of the isothermal dark matter fluctuation or clumps,  $\Phi = \delta\rho_{DM}/\rho_{DM}$ , exceeds unity, a fluctuation collapses in the radiation-dominated epoch and produces a dense dark matter object. They found the final density of the virialized object  $\rho_F$  to be

$$\rho_F \sim 140 \Phi^3 (\Phi + 1) \rho_{eq}, \quad (2)$$

where  $\rho_{eq}$  is equilibrium density.

For axions, a putative dark matter particle, density fluctuations can be very high, possibly spanning the range  $1 < \Phi < 10^4$ . The resultant density in miniclusters can be as much as  $10^{10}$  times larger than the local galactic halo density. The probability at present of an encounter of the earth with such an axion minicluster is 1 per  $10^7$  years with  $\Phi = 1$ . Kolb and Tkachev found two types of axion clumps arising from two kinds of initial perturbations :

- Fluctuations with  $10^{-3} < \Phi < 1$  collapse in the matter-dominated epoch.
- Fluctuations with  $\Phi > 1$  collapse in the radiation-dominated epoch.

If the dark halo is mostly made of neutralinos, then the clumping factor in the MSSM could be less than  $10^9$  for all neutralino masses [4].

## 2. Astrophysical constraints and stability of clumps

Astrophysical constraints can be used to place bounds on the mass of the clumps. The clumps are also stable with regard to main astrophysical disruption processes.

### 2.1. Disk 'puffing' by dark clumps :

As the dark matter clumps traverse the Galactic halo, they will impart energy to the stars residing there. This leads to a gradual puffing up of the disk, and the stars present are heated. In this process, the older stars get heated more than the younger ones. Lacy and Ostriker considered the case of black holes of mass  $10^6 M_\odot$  generating the observed puffing of the galaxy, and concluded that this was the best mechanism to explain the observed amount of 'puffing' of the galactic disk [5]. However, subsequent data revealed that the velocity dispersion of disk stars,  $\sigma$ , may no longer rise as quickly as  $\sqrt{t}$  which was one of Lacy and Ostriker's assumptions. In addition, other sources of heat like spiral density waves and giant molecular clouds may give a better fit to the data. Hence, the Lacy-Ostriker model of black holes generating the observed puffing of the disk is not as convincing now

as it was when first suggested. However, they obtained an upper limit on the density of halo objects of mass  $M$ , which still hold :

$$\Omega_B \leq \Omega_h \min[1, (M / M_{heat})^{-1}], \quad (3)$$

$$\text{where } M_{heat} = 3 \times 10^6 (t_g / 10^{10})^{-1}, \quad (4)$$

where  $t_g$  is the age of the galaxy. This condition must hold, otherwise the disk would be more puffed up than observed. Using this formula, one can obtain an upper limit on the mass of the halo objects in any galaxy. Applying it to the Milky Way yields an upper limit on the mass of dark matter clumps of  $M < 2 \times 10^6 M_\odot$ . Silk and Stebbins obtained, using slightly different arguments, a similar limit of  $10^6 M_\odot$  to avoid the problem of unacceptably heating the disk [2], the general limit for halo objects so as not to heat the disk. However, if the halo objects form pregalactically, which is the case if they are the precursors to the galaxy, then halo objects should have the same order of mass. Thus from an analysis of the gas-rich dwarf galaxy DD0154 one finds  $M \leq 7 \times 10^5 M_\odot$ . For the dwarf galaxy GR8 the limit is  $M \leq 6 \times 10^5 M_\odot$ .

Disk heating can also lead to 'gravitational shocks'. During orbital passage of a dark matter clump through the inner galaxy, the clump is heated. This is a major factor in the disruption of globular star cluster and hence is expected to be a primary factor in the disruption of cold dark matter clumps [6]. This process is considered in the next section.

### 2.2. Dynamical friction :

Gravitational shocking leads to considerable destruction of clumps. The destruction timescale for clumps is given by [6]

$$\frac{t_{dest}}{t_{orbit}} \sim 4 \times 10^4 \left( \frac{10 \text{ pc}}{\langle r_{clump} \rangle} \right) \left( \frac{R_{peri}}{8 \text{ kpc}} \right) \left( \frac{M_{clump}}{10^6 M_\odot} \right) \left( \frac{v_{clump}}{100 \text{ km/s}} \right) \quad (5)$$

where  $M_{bulge}$  is the spherical or disk mass interior to the clump orbit

$\langle r_{clump} \rangle$  is the mean clump radius,

$t_{orbit}$  is the internal orbit time,

$t_{dest}$  is the destruction time scale,

$M_\odot$  is the solar mass,

$M_{clump}$  is the mass of a clump,

$v_{clump}$  is the mean clump velocity,

$R_{peri}$  is the perigalactic distance of the clump orbit.

Numerical simulations give a clump destruction rate of [6]

$$v_{destr}^{clump} \sim \left( \frac{M_{gc}}{M_{clump}} \right)^{1/3} \left( \frac{\rho_{gc}}{\rho_{clump}} \right)^{1/3} v_{destr}^{gc}, \quad (6)$$

where  $v_{dest}^{gc}$  is the present globular cluster destruction rate,  $\rho_{gc}$  is the density of globular clusters and  $M_{gc}$  their mass.

The present globular destruction rate is obtained from numerical simulations including the effect of gravitational shocking by the disk and bulge and evaporation losses. From such calculations it is inferred that this rate is  $10^{-11} \text{ y}^{-1}$ .

Thus, if the mass of the clump  $m_{clump} > 10^4 M_\odot$ , clump destruction is unimportant *via* dynamical processes over the last  $10^{10}$  years [6]. Clumps in the inner few parsec of the halo are likely to have been destroyed, while clump halos in the outer part of the galaxy are likely to have survived intact. If a fraction  $f \sim 10\%$  of the halo has survived in clumps, and if  $\rho_{clump} \sim 10^4 \rho_{halo}$ , then the resultant  $\gamma$  ray signal leads to 10 times larger fluxes than for a uniform dark matter halo.

Tormen *et al* [7] also analysed the survival of substructure in dark matter halos. Using high-resolution  $N$ -body cosmological simulations, they analysed the survival of dark matter satellites falling into larger bodies. They found that all satellites preserve their identity for some time after merger. Satellites with less than a few percent mass of the halo may survive for several billion years, whereas larger satellites rapidly sink into the center of the main halo potential well and soon lose their identity.

### 2.3 Diffusion towards the galactic center :

As halo objects traverse through the halo, they will lose energy and consequently drift towards the Galactic nucleus. It has been shown [5] that halo objects will be dragged into the nucleus by the dynamical friction of the spherical stars from within a galactic radius

$$R_H = (M / 10^6 M_\odot)^{2/3} (t_k / 10^{10} \text{ y})^{2/3} \text{ kpc} \quad (7)$$

and that the total mass dragged into the Galactic nucleus is

$$M_N = 9 \times 10^8 (M / 10^6 M_\odot)^2 \left( \frac{t_k}{10^{10} \text{ y}} \right) \left( \frac{a}{2 \text{ kpc}} \right) \times M_\odot \quad (8)$$

where  $a$  is the halo core radius and all other variables are as defined above.

This places a strong limit on the presence and survival of clumps. However, there are severe caveats on this model. Once two clumps have reached the center, they will form a binary, and should eventually coalesce into a single body due to energy loss. If however, a third dark matter clump arrives before coalescence occurs, then the 'slingshot' mechanism can eject one of the clumps and the remaining clumps could also escape due to the recoil. Most clumps could escape eventual destruction by this method of destruction should not be significant. In addition, dynamical friction.

Thus the cores of the clumps are expected to be stable, although the outer layers may be stripped off by the effects given above. We conclude that a significant fraction of dark matter probably survives in the form of clumps.

### 2.4. Collisions :

Lake [8] analysed the stability of these dark matter clumps against collisions. The time-scale for disruption owing to mutual collisions of uniform-density spheres, yields the critical value for survival *versus* destruction as

$$\rho_c \geq \frac{f^2 \rho_h^2}{27 \rho_{crit}} \quad (9)$$

where  $f$  is the fraction of dark matter in clumps with cluster masses  $M_{cl} \leq M \times 10^6 M_\odot$ ,  $\rho_c$  is the density of WIMPs inside the clump,  $\rho_h$  is the density of halo dark matter, and  $\rho_{crit}$  is the critical density of the Universe.

If the density of the clump is larger than this critical value, then collisions are not a major mechanism for disruption. This is since the lower density clumps cannot survive collisions and are thus destroyed, while the heavier clumps survive such collisions. Instead, when the density of the clumps satisfies this inequality, disruption by tidal shocking becomes the dominant destruction mechanism of the clumps. However, for reasonable parameters, the clumps survive disruption by this mechanism also. Hence, clumps are expected to be stable against tidal disruption.

### 2.5. Experimental searches for dark matter :

Clumping would have a significant impact on searches for dark matter. The nondetection of dark matter candidates may be due to the lower value of the local halo density. An observer in another part of the galaxy where the local halo density was higher would observe a multitude of events that would not be observable at other parts [9]. This holds for direct detection methods. In such methods, the dark matter is detected by direct interactions of the dark matter particle itself with the particles in the detector, analogous to the attempt of 'capturing' it, or observing its trail of escape.

Indirect detection techniques involve the search for signatures of the existence of dark matter rather than attempting to directly capture it, such as searching for the annihilation products of dark matter particles. Such methods would be facilitated by clumping, as a larger number of such products would be observed on Earth in the direction of a clump [9]. For example, the study of the high energy gamma-ray particles produced due to the annihilation of dark matter particles will be much more frequent in clumps of dark matter, and hence the excess production in the direction of clumps can be calculated. These are constrained by the results from experiments such as EGRET (to be explained below), which can thus place limits on the amount of clumping.

## 3. Astrophysical signatures

### 3.1. Dark clumps :

It has been observed that several collections of stars on the sub-galactic scale are dominated by dark matter. This may be taken as already existing experimental evidence in favour

of clumped dark matter. At present, the results are generally approximated by 'clumps' of dark matter within a background uniform halo. Some of the recently discovered dark-matter dominated clumps are :

- Extreme dwarf spheroidal satellites of the Milky Way, Draco and Ursa Minor are dominated by dark matter. They are essentially dark matter clumps. Their existence is difficult to reconcile with Gaussian initial conditions [8].
- The Sagittarius dwarf spheroidal, discovered in 1994, resides in the Milky Way halo, at a distance of about 15 kpc from the centre of the Milky Way. It is situated well inside the galactic halo potential and about 23 kpc from the Sun, and is dark matter dominated [8].
- R C Duncan analyzed the absorption line spectra of the double quasar Q 2345 + 007 and found it to be lensed by a low-luminosity object at  $z = 1.49$  with a mass contained within a volume of lateral extent  $\sim 40 h^{-1}$  kpc [10]. This indicates the existence of large clumps of dark matter in interstellar space.

Berezinsky *et al* [11] showed that the recent MACHOs discovered in the galaxy can be interpreted as dense neutralino objects. However, the gamma-ray flux is many orders of magnitude higher than the observed one [11]. Thus, the observed gamma-ray flux strongly constrains the fraction of dark matter that can have survived in clumps in the case of the neutralino dark matter candidate.

### 3.2. Gamma-ray sources :

Clumps of dark matter could produce gamma-rays and act as gamma-ray sources through the annihilation of WIMPs contained in the clumps of dark matter. Lake also showed that the clumps would survive collisions with one another and the disk [8]. He showed how several light sources in the Cos B catalogue of gamma-ray sources could be candidates of gamma-ray producing dark matter clumps. He proposed Geminga, the second-brightest gamma-ray source above 50 MeV as a clump of dark matter.

### 3.3. Gamma-ray halo :

There is strong statistical support from EGRET (Energetic Gamma-Ray Experiment Telescope) data for the existence of a gamma-ray halo surrounding the galaxy. It has been suggested that this halo was the result of annihilations of halo dark matter particles. Bergstrom, Edsjo and P Ullio set forth a model involving moderately clumped neutralinos [4,12].

In this model, the gamma rays are produced by the pair annihilation of neutralinos  $\tilde{\chi}$ , the lightest supersymmetric particle in the Minimal Supersymmetric Standard Model (MSSM). They assumed that the average clump mass distribution follows the smooth component distribution. It was not possible to reproduce the energy spectrum (antiproton flux vs energy) assuming a smooth dark matter halo. But it was compatible with the clumped dark matter scenario.

A strong excess of gamma rays with energy above 55 MeV was also detected towards the galactic centre of the Milky Way. This can be explained by the occurrence of a higher degree of clumping towards the galactic centre. The degree of clumping required implies a measurable excess of antiprotons at low energies. There is support for this from recent BESS measurements.

Thus the measured excess of cosmic gamma-rays and antiprotons could be explained by invoking the existence of clumped dark matter. Bergström *et al* [12] pointed out the upcoming experiments would be able to rule out or more strongly confirm this theory.

The integrated  $\gamma$ -ray flux above an energy threshold  $E_{th}$  is given by

$$\phi_{\gamma}(E_{th}, \Delta\Omega, \psi) \sim 1.87 \times 10^{-8} S(E_{th}) \times \langle J(\psi) \rangle (\Delta\Omega) \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (10)$$

where  $S(E_{th})$  is a particle physics dependant term. The dependance of the flux on the dark matter distribution is contained in the  $\langle J(\psi) \rangle (\Delta\Omega)$  term. This contribution of the clumps to the flux of gamma-rays, a measure of the contribution of clumps to the gamma-ray halo of the galaxy, is given by [13]

$$\langle J(\psi) \rangle_{cl} (\Delta\Omega) = \frac{1}{8.5 \text{ kpc}} \frac{1}{\Delta\Omega} f \delta \int_{\Delta\Omega} d\Omega' \int_{line \ of \ sight} dl \left( \frac{\rho(l, \psi')}{0.3 \text{ GeV/cm}^3} \right), \quad (11)$$

where  $\Delta\Omega$  is the angular acceptance of the detector pointing in a direction which forms an angle  $\psi$  with respect to the galactic center and  $f$  is the fraction of dark matter concentrated in clumps and  $\rho(l, \psi)$  is the dark matter distribution at the point  $(l, \psi)$ . In the smooth case the dependence is quadratic in the density  $\rho$ . The relative strengths of the clumped components depends on both the halo profile and the product of the halo fraction in clumps and their overdensity  $f \delta$ .

It is observed that there is a discrepancy between the 2.75 power law expected from a model of diffuse galactic background and the results obtained by EGRET. The dark matter signal carrying an excess of  $\gamma$  rays from a few GeV to the mass of the dark matter particles  $M_{\chi}$  may explain this discrepancy. In addition the smooth dark matter halo models cannot reproduce the EGRET data, but this is possible with clumped dark matter models.

The new high energy cosmic gamma-ray detectors both ground and space-based shall have the possibility of searching for dark matter signals [14].

### 3.4. Antiproton flux :

It has been suggested that the antiproton flux in cosmic rays may be due to annihilating dark matter. In addition, the antiproton flux is able to place constraints on the level of clumping as shown by Mitsui *et al* [15]. The antiproton flux

in cosmic rays may be due to annihilating neutralino dark matter, evaporating primordial black holes (PBH's) and superconducting strings. The annihilation of neutralinos may produce a detectable flux of antiprotons. This process occurs *via* the path

$$\begin{aligned} \Xi\bar{\Xi} &\rightarrow q, \text{ leptons and other particles} \\ &\rightarrow \bar{p} + \text{other particles.} \end{aligned} \quad (12)$$

Using a standard model in the minimal  $N = 1$  supergravity with radiative breaking of the electroweak gauge symmetry, Berezhinsky *et al* [16] pointed out that the expected value of  $\Omega_{\Xi}h^2$  lies in the range of  $0.2 + -0.1$  in most cosmological models from the viewpoint of the age of the Universe. Thus, Mitsui *et al* [15] took  $\Omega_{\Xi}h^2 = 0.18$ . Now, neutralinos with this value are most likely pure binos, which predominantly annihilate into bottom quark pairs  $b\bar{b}$  or tau lepton pairs  $\tau^+\tau^-$ . The  $b\bar{b}$  pairs can give antiprotons, but the tau leptons do not. Utilising a Monte Carlo simulation based on the diffusion model utilising source spectra of  $\bar{p}$  obtained from the fragmentation functions constructed from JETSET, Mitsui *et al* found that the annihilation rate of neutralinos per unit volume ( $S$ ) was proportional to the square of the local halo dark matter density  $\rho_{\Xi}$ , but that for PBH's, the relation was linear.

They also obtained fluxes of antiprotons that are too small if a homogenous, isothermal and spherical dark matter distribution of density  $\rho = 0.3 \text{ GeV/cm}^3$  is assumed. They noted three cases, however, where the dark matter density would be enhanced, leading to a larger antiproton flux.

Firstly, the Galactic halo may be flattened towards the galactic disk. This could lead to an enhancement of the local halo density by a factor of 2, leading thereby to an enhancement in the antiproton flux by a factor of 4.

Secondly, an NGS (non-dissipative gravitational singularity) may reside at the galactic centre, leading thereby to a halo distribution of

$$\rho_h(r) = \rho_{h\odot}(r/r_{\odot})^{-1.8} \text{ for } r > 0.1 \text{ pc}, \quad (13)$$

where  $\rho_h(r)$  is the local halo density,  $r_{\odot}$  is the galactic radius of the Sun and  $\rho_{h\odot}$  is the halo density near the Sun. This would lead to an enhanced antiproton flux, possibly by a factor of 200.

Thirdly, if the halo consists of clumps of dark matter, enhancements of  $10^2$ – $10^9$  may be generated in the early universe. If a few per cent of the neutralino dark matter is in such clumps, then the antiproton flux would be enhanced by a factor of 20.

#### 4. Geophysical signatures

Possible geophysical signatures of clumping include such large-scale effects as volcanism and mass extinctions and the possible creation of defects in mica.

##### 4.1. Volcanism :

Volcanism is one of the means through which heat generated inside the Earth escapes it. The primary sources of heat in the Earth are believed to be radioactivity and primordial accretional heat. As per conventional wisdom these are the only major sources of heat in the Earth. In the case of special planets like Io, other sources like tidal heating can become significant. Recently, it has been shown by two of the authors [17] that dark matter accumulations inside the Earth could produce huge amount of heat with drastic consequences. They proposed that the annihilation heat due to dark matter could be a new source of heat.

Here the term 'volcanogenic dark matter' is used to refer to the volcanism arising due to the capture and annihilation of dark matter inside the earth. This process occurs *via* several stages : Firstly, the capture of dark matter, followed by the accumulation of the captured dark matter in the centre of the Earth and the annihilation of the same. This then leads to plume formation *via* the process outlined below. The plume, on reaching the surface, leads to massive volcanism of the flood basaltic type.

##### 4.1.1. Capture of dark matter :

The capture of dark matter particles by the Earth and planets was first analysed by Press and Spergel [18]. This capture of dark matter particles was investigated on account of the neutrinos and other annihilation products produced. These products are currently the subject of ongoing experiments [19]. Krauss *et al* investigated the neutrinos produced by captured dark matter particles, with scalar or Dirac neutrinos as examples. They obtained greatly enhanced capture rates for masses greater than 12 GeV, and used the luminosity of Uranus to place constraints on dark matter candidates. Upgoing muons produced by accumulated dark matter inside Earth and Sun have also been the subject of investigation [21].

Subsequently, Gould [22] obtained greatly improved formulae with enhanced capture rates. The Gould formula for the capture is

$$\dot{N}E = (4.0 \times 10^{16} \text{ sec}^{-1}) \bar{\rho}_{0.4} \frac{\mu}{\mu_+^2} Q^2 f \left( 1 - \frac{1 - e^{-A^2}}{A^2} |\xi_1(A)| \right) \quad (14)$$

where  $\bar{\rho}_{0.4}$  is the halo WIMP density normalized to  $0.4 \text{ GeV cm}^{-3}$ ,  $Q = N - (1 - 4 \sin^2 \theta_w) Z \sim N - 0.124Z$ ,  $f$  is the fraction of the Earth's mass due to this element,  $A^2 = (3v^2\mu) / (2\bar{v}^2\bar{\mu}_-)$ ,  $\mu = m_X / m_N$ ,  $\mu_+ = (\mu + 1) / 2$ ,  $\mu_- = (\mu - 1) / 2$ ,  $\xi_1(A)$  is a correction factor,  $v$  = escape velocity at the shell of Earth material,  $\bar{v} = 3kT_w / m_X = 300 \text{ kms}^{-1}$  is the velocity dispersion, and  $\hat{\phi} = v^2 / v_{\text{esc}}^2$  is the dimensionless gravitational potential.

This formula neglected the effect of the finite optical depth of the Earth. If this effect is taken into account,

multiple collisions occur, and this enhances the capture by a factor of  $5 - 30 \times$  [23]. Since the Earth is in the potential well of the Sun, the WIMPs actually move faster, making them more difficult to capture directly. Gravitational diffusion however, leads to an increase in the phase-space density of free-space WIMPs due to encounters with the Earth, Jupiter and Venus, so that direct capture of bound and unbound WIMPs is approximately equal to the case of direct capture in free space [24]. This means that the formula given above holds good. Gould showed that indirect capture, namely the capture of WIMPs that are in Solar orbits, was insignificant [24]. Gould also obtained a high-precision WIMP-capture formula for the Sun [25].

#### 4.1.2. Annihilation of dark matter :

This dark matter that is captured, gradually drifts towards the centre of the Earth. This process occurs because the WIMPs lose energy. Here, they accumulate till the critical threshold is crossed, beyond which annihilation becomes very important. Above this threshold, virtually all the WIMPs captured are annihilated. In the WIMP mass range  $15 \text{ GeV} - 100 \text{ GeV}$ , the Gould formula yields total capture rates of the order of  $10^{17} \text{ sec}^{-1}$  to  $10^{18} \text{ sec}^{-1}$ . According to the Gould equation above, this yields  $Q_E \sim 10^8 \text{ W} - 10^{10} \text{ W}$  for a uniform density distribution.

Interestingly intriguing signatures of a dark matter WIMP have been recently obtained at  $56 \text{ GeV}$  [1]. This mass of WIMP, nearly the same as that of iron, would lead to a resonant enhancement in the capture of WIMPs by Earth. The consequence would be an increase in the heat production of the Earth, and this would be in support of our model calculations.

#### 4.1.3. Creation of plume :

In case of uniformly distributed dark matter, the dark matter heat production is much less than the annual geothermic heat output of  $4 \times 10^{12} \text{ W}$ . However, during the passage of a clump core, the heat production due to annihilating dark matter exceeds that due to other sources by several orders of magnitude. What would be the consequence of these vast amounts of heat?

As per conventional theory, this would lead to the creation of what are referred to as 'deep mantle plumes'. As per standard geothermologic models, the lowest layer of the mantle (called the D" layer) absorbs heat from the core, thereby decreasing in density. Eventually, once a critical minimum density is crossed, this D" layer breaks up into rising plumes. These plumes are an efficient way of heat transfer. Ultimately, the largest plumes are capable of reaching the surface.

#### 4.1.4. Flood basalt volcanism and geomagnetic reversals :

On arrival at the surface, the plume will melt its way through the crust, leading to initial explosive volcanism (due to the molten crust) followed by a much longer period of flood basaltic volcanism. As is observed from the vast relics left

behind by these episodes, such volcanism is known to be the most extensive form of volcanism in the world. Examples are the massive Deccan flood basalt volcanic province, the Siberian flood basalt volcanic region, and the Brazilian flood basalt zone. Many such flood basalt episodes occur simultaneous to major mass extinctions of life. Much evidence of a link between these volcanic episodes and the concordant mass extinctions has been established [17].

In addition, the large quantities of heat produced inside the core are capable of leading to geomagnetic reversals. The rise of temperature inside the core leads to an instability in the generation of the magnetic field, which may lead to geomagnetic reversals.

A very attractive feature of this model is that it can explain the 30 million year periodicity in the record of mass extinctions, the 30 million year periodicity observed in the periodicity of flood basalt volcanism, and the 30 million year periodicity calculated for the crossing of clumps (obtained from the models of clumping).

#### 4.2. Defects in mica :

Baltz *et al* [26] studied the effect of dark matter on mica. They studied two models of the density profiles for the clumped fraction of the dark matter halo, namely the Hernquist profile and the Navarro, French and White (NFW) profiles. The Hernquist profile is given by

$$\rho(r) = \frac{M}{2\pi} \frac{1}{r(r+a)^3}, \quad (15)$$

$$\phi(r) = -\frac{GM}{r+a} \quad (16)$$

The NFW profile is given by

$$\rho(r) = \frac{M}{4\pi} \frac{1}{r(r+a)^2} \quad (17)$$

$$\phi(r) = -\frac{GM}{r} \ln\left(1 + \frac{r}{a}\right) \quad (18)$$

where  $a$  is the scale radius,  $M$  the mass parameter,  $\rho$  the density,  $\phi$  the gravitational potential, and  $r$  the radius at the point under consideration.

Now, the rate at which defects accumulate in mica is a function of the angle  $\alpha$  which the incident particle makes with the cleavage plane. Monte Carlo simulations show that the rate at which tracks accumulate,  $\frac{dN}{dt}$  is well approximated by [26] :

$$\frac{dN(\alpha)}{dt} = c_0 + c_1 |\cos \alpha|, \quad (19)$$

where  $c_0, c_1$  are functions of the WIMP mass, the dispersion velocity of the halo and the velocity of the earth through the halo. They were calculated assuming that the mica has remained fixed in position relative to the incident WIMPs. In geophysical terms, this corresponds to assuming that the mica has remained geologically stationary, in other words

the phenomenon of continental drift has been ignored. They took, as an example, a single  $10^6 M_\odot$  clump interacting with the earth at different times from the formation of the mica, taken to be 440 million years ago, and the present. Experiments using neutrons instead of WIMPs as the incident particles conformed to this model, and hence it is reasonable.

Baltz *et al* [26] took for their simulations, a mica age of 440 million years, which corresponds to two galactic years, *i.e.* two rotations of the earth about the galactic centre. For  $A = 10$ , where  $A$  is the mass number, they noticed a substantial change in the signal of the clump compared to the background. At  $A = 100$ , the change in the signal is much more substantial. Most of the forward angle show a pronounced change in the signal. In the clumped case, the signal is much larger and the maximum and minimum directions are very different from the non-clumped case. For  $A = 1000$ , the signal is ten times larger than the non-clumped case [26]. The signal from a clump encounter 440 My ago appears to be oriented in the same direction for all incident directions. This circumstance arises since the North American craton was situated at the equator at this time. For signals occurring 220 My ago, this degeneracy is broken as this continent had by that time moved away from the equator. The authors suggested using mica samples from different locations from different continents, of different ages and different orientations to obtain a large amount of information about the nature of the clumping of the dark matter in the halo [26].

## 5. Conclusion

In addition to arising naturally within cosmological dark matter models, clumped dark matter would be stable on astrophysical time scales and clumps are likely to have survived to the present epoch. The existence of clumped dark matter also would solve many problems in astrophysics and geology that find either difficult or no explanation at all within conventional frameworks. Such cases include the galactic gamma-ray halo and the periodicity in terrestrial flood basalt volcanism. Annihilation of clumped dark matter should also be treated as a new source of heat in planetary bodies which may have observable consequences. In addition, they may have already been discovered in the form of dwarf spheroidals. The significance of clumped dark matter is such that it calls for further studies.

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